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# ENHANCING POWER QUALITY BY COMPENSATING REACTIVE POWER USING MULTILEVEL STATCOM

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## ABSTRACT

Flexible AC transmission systems (FACTS) has become the technology of choice in voltage control, reactive/active power flow control, transient and steady-state stabilization that improves the operation and functionality of existing power transmission and distribution system. Static synchronous compensator (STATCOM) is one of the new-generation FACTS devices, and recognized to be one of the key technologies in future power system because of the instantaneous compensating of voltage from it to the transmission line or vise versa. This study explains the design of a cascaded multilevel STATCOM with the necessary controllers and equipment's to compensate the reactive power of AC transmission line system. The cascaded multilevel STATCOM is a multilevel voltage source converter based static synchronous compensator (STATCOM). This technique is performed in a MATLAB Simulink environment. The new strategy of compensation is proposed to decrease the voltage fluctuation such as sag and swell. Also the voltage harmonics in the transmission system is isolated. The cascaded multilevel STATCOM can be used in a point of common coupling (PCC) for improving power quality. It is modeled and simulated using proposed control strategy and the performance is compared by applying it to a 133kv line with and without STATCOM. Harmonic analysis is also proved in this study and based on the total harmonic distribution (THD) calculations.

**KEYWORDS:** Power Quality, Reactive POWER Compensation, Multilevel STATCOM, Total Harmonic Distribution

## INTRODUCTION

### Power Quality Issues

Power quality is a simple term, yet it describes a multitude of issues that are found in any electrical power system and is a subjective term. The concept of good and bad power depends on the end user. If a piece of equipment functions satisfactorily, the user feels that the power is good. If the equipment does not function as intended or fails prematurely, there is a feeling that the power is bad. In between these limits, several grades or layers of power quality may exist, depending on the perspective of the power user. Understanding power quality issues is a good starting point for solving any power quality problem. Figure 1 provides an overview of the power quality issues [1-2] [23].

- **Power Frequency Disturbances**

Power frequency disturbances are low-frequency phenomena that result in voltage sags or swells. These may be source or load generated due to faults or switching operations in a power system.

- **Power System Transients**

Power system transients are fast, short-duration events that produce distortions such as notching, ringing, and impulse. The mechanisms by which transient energy is propagated in power lines, transferred to other electrical circuits, and eventually dissipated are different from the factors that affect power frequency disturbances [24].

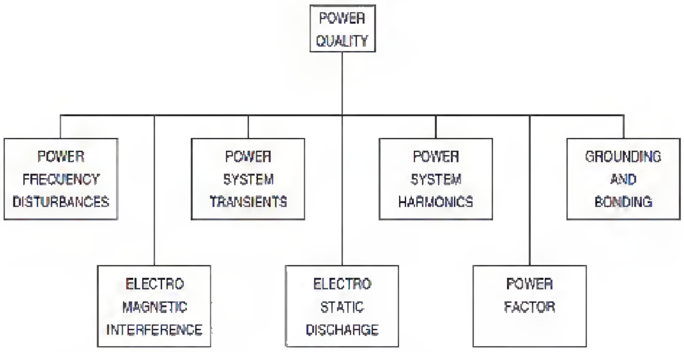


**Figure 1: Power Quality Concerns [37]**

- **Power System Harmonics**

Power system harmonics are low-frequency phenomena characterized by waveform distortion, which introduces harmonic frequency components. Voltage and current harmonics have undesirable effects on power system operation and power system components. In some instances, interaction between the harmonics and the power system parameters (R–L–C) can cause harmonics to multiply with severe consequences [3-9].

- **Electromagnetic Interference**

Electromagnetic interference (EMI) refers to the interaction between electric and magnetic fields and sensitive electronic circuits and devices. EMI is predominantly a high-frequency phenomenon. The mechanism of coupling EMI to sensitive devices is different from that for power frequency disturbances and electrical transients.

- **Radio Frequency Interference**

Radio frequency interference (RFI) is the interaction between conductor radiated radio frequency fields and sensitive data and communication equipment. It is convenient to include RFI in the category of EMI, but the two phenomena are distinct.

- **Power Factor**

Power factor is included for the sake of completing the power quality discussion. In some cases, low power factor is responsible for equipment damage due to component overload. For the most part, power factor is an economic issue in the operation of a power system [24].

**Reactive Power Compensation**

The long switching periods and discrete operation make them difficult to handle the frequently changed loads smoothly and damp out the transient oscillations quickly [3-5]. In order to compensate these drawbacks, large operational margins and redundancies are maintained to protect the system from dynamic variation and recover from faults. This not only increases the cost and lowers the efficiency, but also increases the complexity of the system and augments the

difficulty of operation and control [6-9]. Severe black-outs happened recently in power grids worldwide and these have revealed that conventional transmission systems are unable to manage the control requirements of the complicated interconnections and variable power flow. The demands of lower power losses, faster response to system parameter change, and higher stability of system have stimulated the development of the Flexible AC Transmission systems (FACTS) [23]. The term FACTS covers several power electronics based systems used for AC power transmission and distribution. Given the nature of power electronics equipment, FACTS solutions will be particularly justifiable in applications requiring one or more of the following qualities, Rapid dynamic response, Ability for frequent variations in output, and Smoothly adjustable output. With FACTS, the following benefits can be attained in AC systems, Improved power transmission capability, Improved system stability and availability, Improved power quality, Minimized environmental impact, and Minimized transmission losses [9].

**Principle of Operation of STATCOM**

The STATCOM is basically a DC-AC voltage source converter with an energy storage unit, usually a DC capacitor. It operates as a controlled Synchronous Voltage Source (SVS) connected to the line through a coupling transformer. Figure 2 shows the schematic configuration of STATCOM. The controlled output voltage is maintained in phase with the line voltage, and can be controlled to draw either capacitive or inductive current from the line in a similar manner of a synchronous condenser, but much more rapidly. The VSC is used a forced commutated power electronic devices (GTOs or IGBTs) to synthesize the voltage from a DC voltage source. The operating principle of STAT ACOM is explained in figure 2 [10].

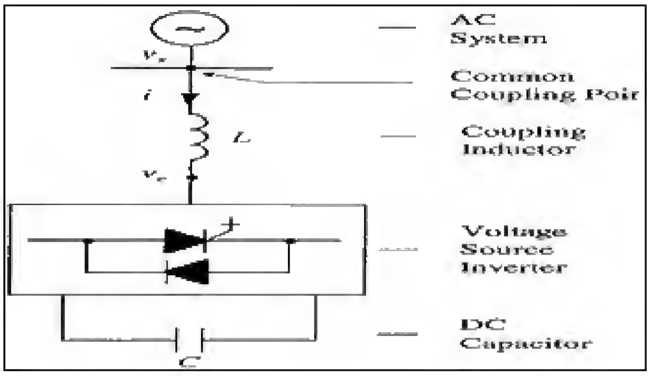


**Figure 2: Single-Line Diagram of the STATCOM System**

It can be seen that if $V_c$>$V_s$ then the reactive current (i) flows from the converter to the ac system through the coupling transformer by injecting reactive power to the ac system. On the other hand, if $V_c$<$V_s$then current (i) flows from ac system to the converter by absorbing reactive power from the system. Finally, if $V_c$=$V_s$then there is no exchange of reactive power. The amount of reactive power exchange is given by:

$$Q_C = V_S \frac{V_S - V_C}{X} \tag{1}$$

Where

$V_s$: Magnitude of system Voltage.

$V_c$: Magnitude of STATCOM output voltage.

X: Equivalent impedance between STATCOM and the system.

**Cascaded H-Bridge Multilevel Inverter (CHB)**

A cascaded multi-level converter circuit is shown in figure 3. It is a three phase VSC which comprises of three single phases and each phase consists of H-bridges connected in series. The three phases in the converter are star connected. Each single phase H-bridge converter has two arms consisting of two pairsof GTO and diode connected in anti-parallel. Each H-bridge has its own capacitor, acting as a voltage source. Individual capacitors of same capacitance are selected to meet the economic and harmonic criteria. The Voltage Source Converter (VSC) is connected to the power system via a shunt connected transformer, as the STATCOM. The real power exchange between the VSC and the power system can he controlled by altering the phase angle between the output voltage and the ac system voltage. If the output voltage is made to lead the ac system voltage, the VSC supplies real power to the ac power system. If the output voltage is made to lag the ac system voltage, the VSC absorbs real power from the ac power system. An energy supply or absorb device is required for the real power exchange [13]. This role is played by another VSC or a dc energy storage device like a super-conducting magnet or a battery. The exchange of real and reactive power is implemented individually. The VA rating of the VSC is determined by the product of the power system voltage and the maximum output current. . Some of the main benefits of this VSC-based STATCOM system design are as follows, Rapid response to system disturbances, Smooth voltage control over a wide range of operating conditions, and Significant amount of built-in redundancy [23]. The peak output voltage of ST A TCOM is N times to that of the capacitor voltage, where N is the number of H-bridges in each phase[15-18]. Each H-bridge generates three voltage levels +V dc, 0 and - V dc and the total output voltage of each phase isthe combination of individual H-bridge voltages. ASTATCOM with N converters per phase can synthesize 2N+ 1voltage levels. The output voltage waveform of the cascaded N-level STATCOM depends on the switching pattern, which is controlled by the switching angles of the converters. These switching angles can be independently selected, but appropriate switching angles are required to achieve good quality of the output voltage waveform. By employing SHEM, lower order harmonics can be eliminated in the output waveform. The amplitude of the odd harmonic order of the output voltage with 2N+1 level can be represented using Fourier's series method as in equation 2 [10].

$$V_n = \frac{4V_{dc}}{n\pi}\sum_{k=1}^{N}\cos n\theta_k \tag{2}$$

Where, $V_n$ is the amplitude of voltage harmonic of $n^{th}$ order.,$V_{dc}$ is the DC voltage across the capacitor, $N$ is the number of the bridges in each phase.,$n$ is the odd harmonic order., and $\theta_k$ is the switching angle of the single phase bridge [10].

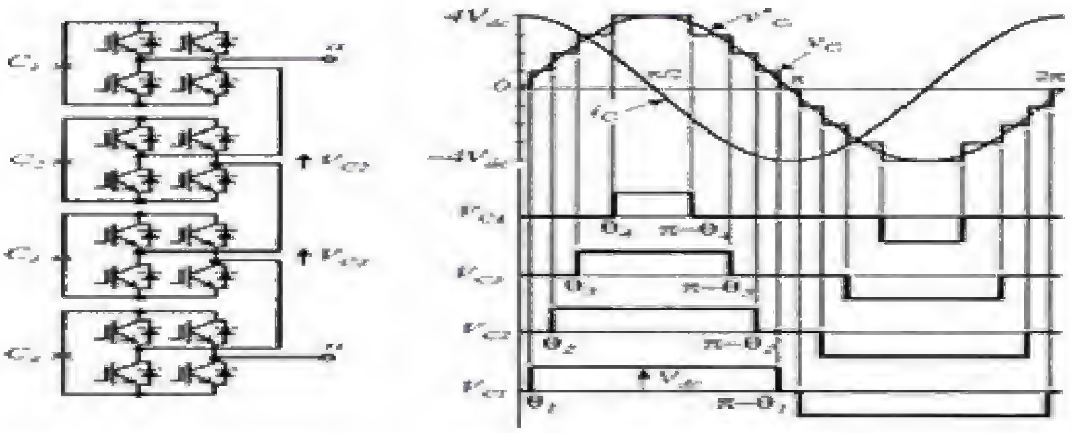

**Figure 3: Single Phase 9 Level H-Bridge Inverter and Switching Strategies [10]**

**STATCOM Controller**

The AC voltage controller generates the desired reactive current reference for the current regulator. In the design of the STATCOM controller, it is essential to have good dynamic response in the transient period and to ensure minimal harmonics at steady state. As shown in figure 4, a transient modulation index controller and a steady-state modulation-index regulator are proposed to achieve the goals of good transient response and minimal steady-state harmonics respectively [12], [14]. Details for the design of transient modulation-index controller, steady state modulation-index regulator, phase locked loop (PLL), abc to dq0 transformation, AC voltage controller, Current regulator, pulse width modulation (PWM) generator are described below [10]:

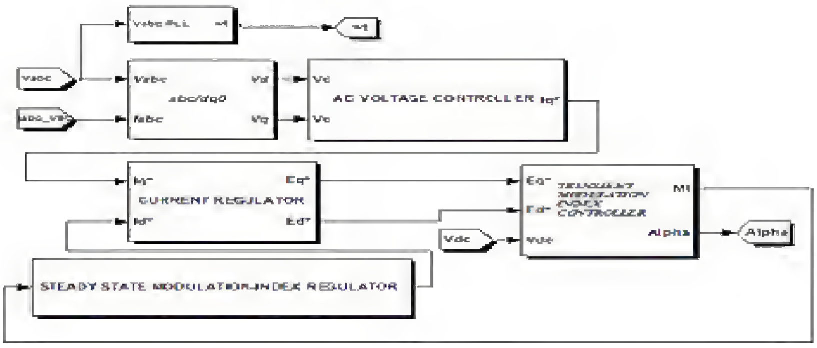


**Figure 4: STATCOM Controller [10]**

- **Phase-Locked Loop**

A phase-locked loop or phase lock loop (PLL) is a control system that generates an output signal whose phase is related to the phase of an input signal.

- **Dqo Transformation**

In electrical engineering, direct–quadrature–zero (or dq0 or dqo) transformation or zero direct–quadrature (or 0dq or odq) transformation is a mathematical transformation that rotates the reference frame of three-phase systems in an effort to simplify the analysis of three phase circuits. It computes the direct axis $V_d$, quadrature axis $V_q$, and zero sequence $V_0$quantities in a two axis rotating reference frame according to the Park's Transformation shown below.

$$V_d = \frac{2}{3}\left[V_a \sin(wt) + V_b \sin\left(wt - \frac{2\pi}{3}\right) + V_c \sin\left(wt + \frac{2\pi}{3}\right)\right] \quad (3)$$

$$V_q = \frac{2}{3}\left[V_a \cos(wt) + V_b \cos\left(wt - \frac{2\pi}{3}\right) + V_c \cos\left(wt + \frac{2\pi}{3}\right)\right] \quad (4)$$

From equation (3) and equation (4) to give equation (5)

$$V_0 = \frac{1}{3}[V_a + V_b + V_c] \quad (5)$$

Where (w = rotating speed (rad/sec) of the rotating frame.

- **AC Voltage Controller and Current Regulator**

The AC Voltage controller converts $V_d, V_q$ into reference reactive current ($I_q^*$) using appropriate is given by equation 6 PI Controllers as shown in figure 4.

$$i_q^* = G_1(s)[V_{rms} - V_{rms}^*] \quad (6)$$

$$G(s) = K_1 + \frac{K_2}{s} \quad (7)$$

Similarly Current regulator uses reference reactive current $I_q^*$ and reference direct current $I_d^*$along with PI Controllers to generate reference direct and quadrature voltages $E_d^*$ ,$E_q^*$respectively.

$$E_d^* = -wL_f i_q + V_{dc} - x_1 \quad (8)$$

Where

$$x_1 = G_2(s)[i_d^* - i_d] \quad (9)$$

$$G_2(s) = K_3 + \frac{K_4}{s} \quad (10)$$

Where, $L_f$ is leakage inductance.$V_{dc}$ is capacitor voltage.

- **Transient Modulation-Index Controller**

STATCOM output voltage is proportional to the product of modulation-index (MI) and$V_{dc}$. Since it is impossible to change $V_{dc}$instantaneously, it is desirable to adjust the MI in the transient period such that the PCC bus voltage can be regulated efficiently. Thus, a transient modulation-index controller is proposed to adjust the MI rapidly in the transient period.

$$MI = \frac{\sqrt{E_d^* + E_q^*}}{KV_{dc}} \quad (11)$$

$$\propto = \tan^{-1}\left(\frac{E_q^*}{E_d^*}\right) \quad (12)$$

- **Steady-State Modulation-Index Regulator**

A steady-state modulation-index regulator is proposed to drive the modulation index to the pre-set value (MI*=1 in this work) at steady state through the action of a PI controller

- **PI Controller**

A PI Controller (proportional-integral controller) is a special case of the PID controller in which the derivative (D) of the error is not used. PI controller generates a gated command to operate theconverters and to compensate the error, which has beencalculated by comparing defined values against measuredvalues for both reactive and real powers [19 -22].

**Structure of the Simulated Compensator Design System**

Here, we enhance the power quality using the method of compensate of reactive power by the MATLAB Simulink technology. The compensating of reactive power produced to enhance the power quality because this enhancement means maintain one quantity of the two quantities of the complex power. In this method of compensation, the use of cascaded multilevel STATCOM is very efficient to compensate the reactive power because the good response and sense of STATCOM.As shown in figure 5 the power system simulated design is consist of the following parts

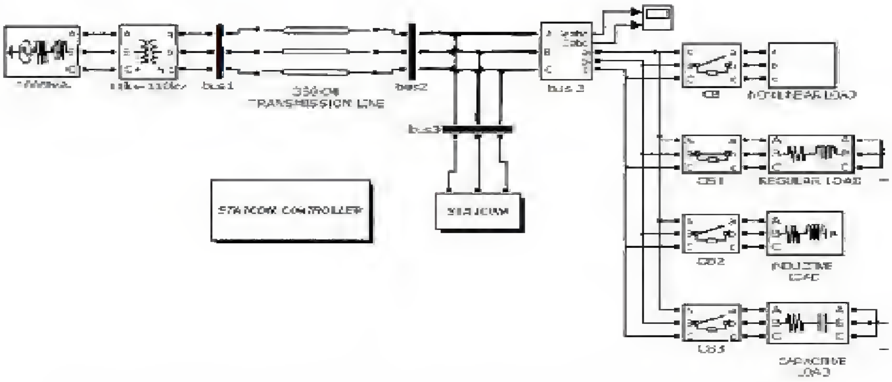


**Figure 5: MATLAB Implementation of Power System with STATCOM**

**System Parameters**

- **Source**

The source is a plant of generators provides a 133kv, 50 hertz frequency to the transmission line.

- **Load**

The load chosen is consists of a nonlinear, inductive, capacitive, and normal load. These loads are changed from one type to another for each interval to see the performance of the compensation system.

- **Transmission Line**

The transmission line is of length 200 Km and has two bus bar, first bus bar near the source to measure the magnitude of phase to ground voltage, the second bus bar near the load to measure the phase to phase voltage

- **Cascaded Multilevel STATCOM Compensator**

A cascaded multilevel STATCOM compensator and its controller are connected to the transmission line of the electrical power system through a three phase bus bar. Each bus bar consists of a c.t. transformer, then the sum is a three c.t. transformers. The cascaded multilevel STATCOM comprises three phase voltage source converter contain from three single phase, each single phase contains on h-bridge connected series. The three phases in the converter are star connected. Each single phase h-bridge converter has two arms consisting of a GTO and diode connected in anti-parallel. Any one of h-bridges has capacitor act s as a voltage source. Individual capacitors of same capacitance are selected to meet the economic and harmonic criteria.

## RESULTS

When the system is worked the Simulink system we observed changes the value of voltage and current before and after connected the STATCOM section. We obtained the result in output system for voltage and current are changing according to the type of the loads used in every moment interval that means we used nonlinear, inductive, capacitive and normal load in the load section. When the inductance is used in the load section, it decreased the level of voltage in the output. While when we used the capacitor in the load section, it increased the level of voltage in the output in the same simulation system by used STATCOM technique. The performance of cascaded multilevel STATCOM technique when the load is inductive is injected of the reactive power to compensate the decrease of reactive power in system. But in the capacitive load the performance of cascaded multilevel STATCOM is to absorb the reactive power from the system.

Figure 6 shows the output voltage in above part of figure and the output current in below part of figure for the simulation system. The output voltage for output system is swing or changing for one or more phases in transmission electrical line but in this figure swing in waveform for first phase decreased it because the loads are changed by resistance, inductance, and nonlinear. The output current is balance and equals all phase's waveform in the output system without any procedure on it that means without STATCOM.

Figure 7 shows the output voltage in above the part of figure and the output current in below the part of figure the simulation system with STATCOM technique. The output voltage for the simulation system connected with STATCOM technique the waveform on the load the decreased or decreased the output voltage compensator the value of voltage by STATCOM to inject or absorb for output voltage for regular output the system.

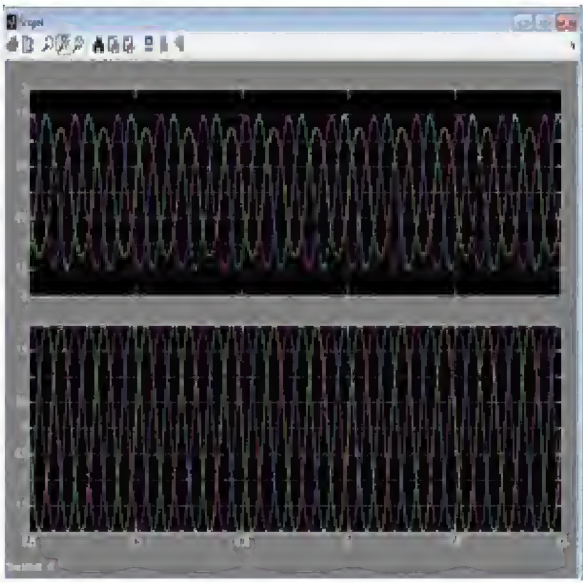

**Figure 6: Output Voltage and Current of the Power System without STATCOM**

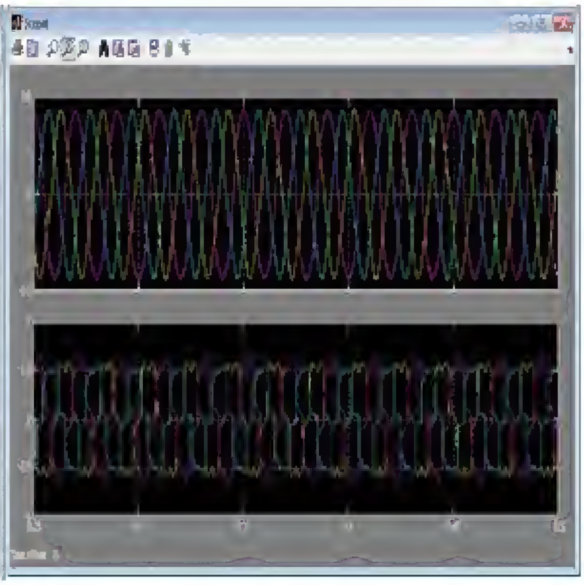

**Figure 7: Output Voltage and Current of the Power System with STATCOM**

**Total Harmonic Distribution**

Inthe analysis of the voltage quality waveform obtained in our work, we got the total harmonic distribution is decreased in this simulation depends on the use of a transient modulation index regulator, these achieve the goal of minimal harmonics. The THD of output voltage is calculated and compared between the results of the system with and without cascaded multilevel STSTCOM. The THD before the cascaded multilevel STATCOM is 13.46% as shown in figure 8, and after connected the cascaded multilevel STATCOM is 8.46% as shown in figure 9. In other side, this results compared with the results of other works of a low level STATCOM system that means the THD is reduced in the new technology of $9^{th}$ level with respect to the technology of $7^{th}$ or $5^{th}$ level as shown in Table.I.

For analyzing the quality of the voltage waveform total harmonic distortion calculations are performed using equation (13).

$$THD = \frac{\sqrt{\sum_{k=2}^{\infty} |V_k|}}{|V_1|} \tag{13}$$

**Table 1: THD Results Comparison**

| S/No | Level | THD |
|---|---|---|
| 1 | 5th Level | 24.92 |
| 2 | 7th Level | 15.89 |
| 3 | 9th Level | 8.45 |

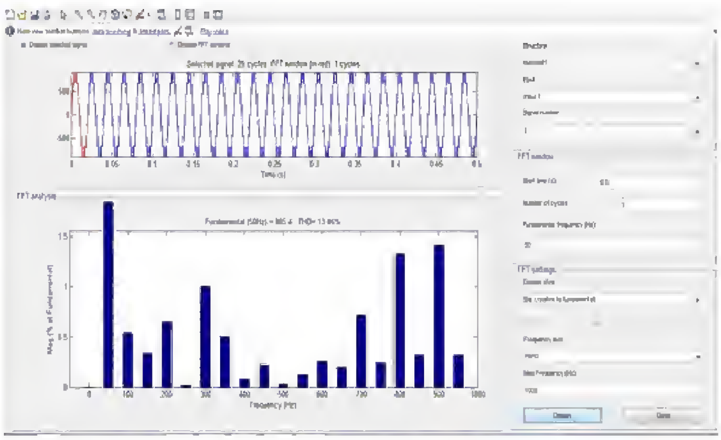

**Figure 8: THD Analysis of Output Voltage Waveform without STATCOM**

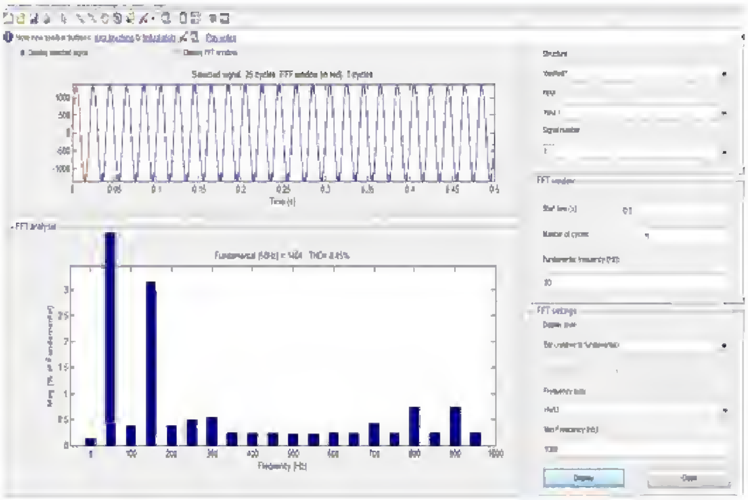

**Figure 9: THD Analysis of Output Voltage Waveform with STATCOM**

## CONCLUSIONS

The STATCOM with controller employing the direct control strategy is able to maintain the voltage balance under various load conditions or other effective in the state load. In the other word, the STATCOM can be enhancement the stability performance for electric power system. The new strategy of the design is reduced the current and voltage harmonics in the transmission system.That means the THD is reduced in the new technology of $9^{th}$ level with respect to the technology of $7^{th}$ or $5^{th}$ level.

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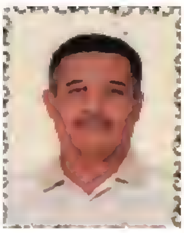

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